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TITLE: DESIGN AND TESTING OF A PROTOTYPE WATER-COOLED VACUUM INTERRUPTER FOR USE IN SUPERCONDUCTING MAGNET PROTECTION CIRCUITS

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AUTHOR(S): W. M. Parsons

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DESIGN AND TESTING OF A PROTOTYPE WATER-COOLED VACUUM INTERRUPTER FOR USE IN SUPERCONDUCTING MAGNET PROTECTION CIRCUITS

W. M. Parsons

Los Alamos National Laboratory

Los Alamos, New Mexico 87545 - USA

Abstract. - A water-cooled vacuum interrupter was designed and tested for use at 25 kA and 10 kV. This device is expected to have a lifetime approximately one order of magnitude greater than commercial dc circuit breakers. Testing showed that, although the device could successfully carry and interrupt 25 kA, interruption reliability was only about 95% with a 10 kV recovery voltage. In addition, a structural crack developed in one electrode from either thermal or mechanical stresses or a combination thereof.

INTRODUCTION

The high capital investment of a large superconducting magnet frequently necessitates the inclusion of a protective dump circuit in the system. The most common method for achieving a fast energy dump is to insert a resistor in series with the superconducting magnet. Practically, this energy dump is accomplished by opening a circuit breaker and diverting the magnet current into a dump resistor. The requirements for this circuit breaker are two fold. It must

1. Interrupt the maximum magnet current, I_m, and withstand the recovery voltage produced when this current is diverted into the resistor and
2. Conduct I_m during normal operation of the superconducting magnet.

The first requirement can be satisfied with commercially available dc circuit breakers provided the recovery voltage is limited to 4 kV or less.[1] The second requirement can be satisfied with commercially available dc circuit breakers provided I_m is limited to about 12 kA or less. However, there are no commercial switches able to operate at voltages above 4 kV or at currents above 12 kA. For this reason, Los Alamos has actively been pursuing the development of a single switch capable of satisfying any current and voltage requirement up to 25 kA and 10 kV.

INTERRUPTER DESIGN

Actuator Design - The dc interruption reliability of 18 cm. vacuum interrupters at 2 kA exceeds 99%.[2] This current level was chosen as the design criterion for the continuous current rating of the device. Other criteria for design of the actuator include:

1. An electrical insulation level of 15 kV dc,
2. A contact closing force capability of 900 kg,
3. An average opening speed of 0.6 m/s,
4. A weld-breaking slack cage in the linkage assembly, and
5. A self-generating axial magnetic field coil to improve arc characteristics and interruption performance.

Axial Magnetic Field Coil. Studies [3] [4] show how the interruption performance of a vacuum interrupter improves with the application of an axial magnetic field. Westinghouse Electric Corporation conducted a series of experiments to determine the axial magnetic field required to prevent anode spot formation and thus improve current interruption.[5] The study showed that to maintain a diffuse arc, the minimum field, B_{min}, is given by the empirical equation

$$B_{min}\ (\mathrm{mT}) = 3.1(I - 10), \tag{1}$$

where I is in kiloamperes and B is in milliteslas. In an earlier Los Alamos sponsored study[6], Gorman and Heberlein suggest that

$$B(\mathrm{mT}) = 7(I - 14) \tag{2}$$

for minimum arc voltage and erosion. Yanabu[7] et al., suggest that, for 8.9 cm diameter copper electrodes and currents between 5 and 40 kA, the minimum arc voltage will be achieved when

$$6.0\ \mathrm{mT/kA} < B < 7.5\ \mathrm{mT/kA}\ . \tag{3}$$

This magnetic field can be self-generated or externally generated. In this design, we chose a self-generating field. The high continuous current necessitated the use of an actively cooled coil winding element. The design produced a field given by,

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$$B = 8.4\ \mathrm{mT/kA} \quad . \tag{4}$$

This equation is plotted in Fig. 1 with the previously mentioned field equations. The present field design is somewhat higher than in the Yenabu design and considerably higher than are the minimum levels recommended by Gorman and Heberlein. The assembled actuator with the axial field coil is pictured in Fig. 2.

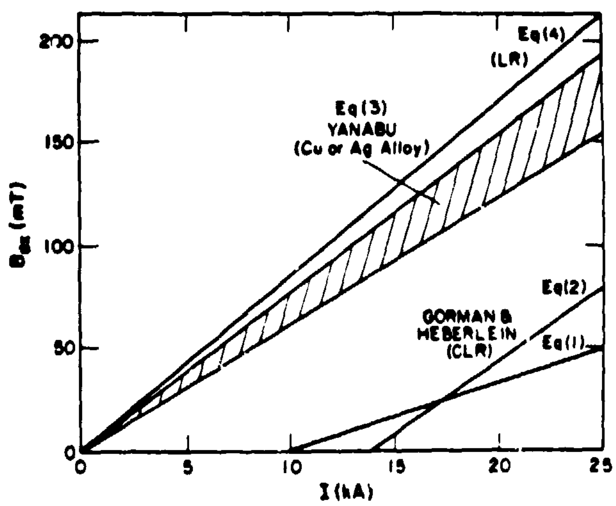

Figure 1. - Axial magnetic field vs current.

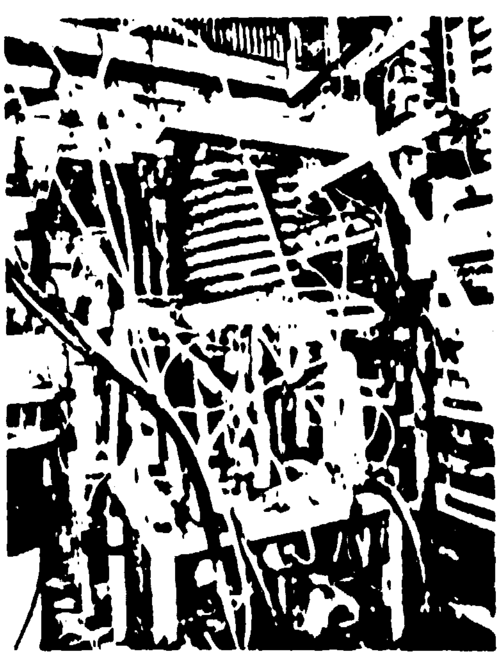

Figure 2. - Assembled actuator.

Interrupter Tube Design - The first water-cooled vacuum interrupter tube tested at Los Alamos was designed and built by Westinghouse Electric Corporation* in 1978. It was constructed primarily to test the water-cooling concept and, aside from the water passages in the stem and contact areas, was a standard design. The contact material was CLR**, a semiresistive, two-phase material developed for low erosion properties. The device could successfully carry currents up to about 10 kA.

With the same general configuration as the first interrupter, a new interrupter was specified in detail by Los Alamos for operation at 25 kA. This interrupter had contacts made of LR**, a material that has erosion characteristics superior to those of copper-bismuth but not CLR. Aside from the change in contact material, the new design differed from the first primarily in stem and water passage sizes. A comparison of these two designs is presented in Table I.

TESTING

Testing of the interrupter system was conducted in three parts. The first group of tests, consisting of pulse interruption tests, verified the system's ability to interrupt high currents at substantial recovery voltages. The second group of tests examined the system's ability to conduct high-level continuous currents. The third group of tests, combining the first and second test sequences, verified interruption ability immediately after conducting high-level continuous currents.

Pulse Interruption Tests - The pulse interruption tests checked the interruption system for reliability before conducting high-level continuous currents. These tests acted as a control to determine any reliability degradation caused by the introduction of the high-level continuous currents. These tests also checked the proper operation and optimization of the

* P. Weyland, Westinghouse Industrial and Government Tube Division, Horseheads, New York.

** Westinghouse Electric Corporation proprietary material.

TABLE I

COMPARISON OF FIRST AND SECOND PROTOTYPE TUBE DESIGNS

	First	Second
Stem o.d. (cm)	2.54	5.08
Stem i.d. (cm)	1.52	2.24
Effective stem area (cm^2)	3.23	16.4
Contact water supply tube i.d. (cm)	0.38	0.91
Internal contact water passage size (cm^2)	0.10	0.41
Flow rate at 275 kPa (ℓ/min)	1.51	13.2
Contact diameter (cm)	11.8	12.8

circuit, including saturable reactors, snubber circuits, and timing sequences.

The circuit breaker performed 88 current interruptions that did not involve preheating. Interrupted currents ranged from 5 to 30 kA while recovery voltages were varied between 2 and 12 kV. The commutation capacitor was varied between 150 and 300 μF during these tests. No failures to interrupt occurred except during several trial tests when the commutation voltage was insufficient to produce the necessary current zero in the vacuum interrupter.

The interrupted current in a typical test was 26 kA and the peak recovery voltage was 10.3 kV. The mean di/dt during commutation was 913 A/μs until the saturable reactor came out of saturation at 760 A. The di/dt was then reduced to 32 A/μs for 24 μs before current zero. The initial rate of rise of recovery voltage was 168 V/μs after interruption.

Continuous Current Tests - The interrupter was tested at current levels between 3 and 27 kA in 3 kA increments with an electrode contact interface force of 4.22 kN. The average resistance of the contacts was measured to be 4 μΩ, only 25% of the 16 μΩ used in the calculations. Examination of the contact surfaces at the end of testing showed shallow melted areas on the faces. This observation is consistent with other studies[8] in which the initiel microscopic bridges between two current carrying surfaces melted to increase their effective interface cross section, thus lowering the bridge resistance.

Hybrid Tests - This experiment combined the pulse interruption tests and the continuous current tests to simulate interruption of a high-level continuous current at high voltage. Figure 3 shows the current through the interrupter during these tests. A total of 87 hybrid tests were performed at currents ranging from 9 to 29 kA. Most of these tests involved a current of 25 kA.

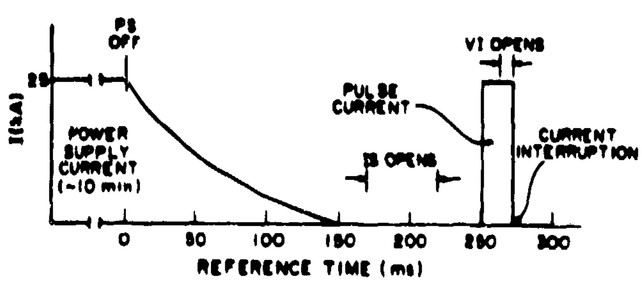

Figure 3. - Current through interrupter during hybrid tests.

There were four restrikes of the vacuum interrupter during this sequence. Two of the restrikes occurred within 1 ms after interruption and were probably a result of thermionic emission from local hot spots created during the closed contact conduction period. The other two restrikes were delayed restrikes and occurred between 70 and 90 ms after interruption.

Delayed restrikes are generally caused by small loose particles being accelerated across the electrode gap by the applied recovery voltage. Several theories explain how this accelerated particle causes breakdown. Cranberg[9] suggests that the impingement of the particle into the opposing electrode may "knock out" another particle with enough energy to cause an avalanche. Slivkov[10] theorized that the accelerated particle may vaporize upon impact, causing breakdown. Other experiments [11] have shown that for large particles, breakdown initiates between the electrode and the particle while the particle is still in flight. The plasma produced by this breakdown may be sufficient to trigger a breakdown across the entire gap. All of the above explanations assume that the particle is initially unattached and show the time required for particle acceleration and subsequent restrike is much shorter than the 70 to 90 ms observed. If we calculate the time required for a particle to move from the upper contact to the lower contact under the influence of gravity, then a travel time of ~45 ms results. The possibility exists that a small molten particle could be jarred loose from a hot spot created during the closed electrode conduction period. This particle, moving primarily under the influence of gravity, would then follow a pattern similar to the last one described.

DISASSEMBLY AND INSPECTION OF TUBE

Figure 4 shows the interrupter electrodes at the end of testing. The small areas melted by high current conduction are evident over approximately 80% of the contact faces. They are most easily seen on the cathode, the electrode to the right, although there is a mate for each area on the anode. We suspect that these areas caused both the fast and delayed restrikes observed during the hybrid tests. Examination of the cathode revealed a crack in an electrode cap. This crack was evidently caused by one or both of two stresses:

1. Thermal stress. The outer edge of the cathode face contains a build-up of contact material that was transferred from the anode during arcing. This buildup produced a local peak in the otherwise flat electrode surface. When the electrodes were brought together, this edge region was the first to make contact and carried some

significant portion of the current. Unfortunately, the edge is not in proximity to most of the internal cooling passages and quite possibly overheated, producing internal stresses that fractured the material.

2. Mechanical stress. If the raised cathode edge is welded to the edge of the anode, then the mechanical force exerted by the actuator during opening could have yielded the material by tensile fracture. This material is designed to be weak in tension to prevent serious contact welding after interrupting heavy fault currents.

CONCLUSIONS

The water-cooled vacuum interrupter appears to have promise as a continuous current, 25 kA interrupter if the restriking and electrode cracking problems can be eliminated. Discussions with Westinghouse personnel have led to a modified interrupter design that should eliminate or minimize the problems. These modifications include

1. Increasing the percentage of copper in the electrode cap face to reduce electrical and thermal resistivity.
2. Changing the composition of the electrode cap sidewall from a copper based material to pure copper. This should eliminate electrode cracking in this area by reducing electrical heating and increasing thermal conduction.
3. Changing the geometry of the electrode face from a flat profile to a face with a raised annular ring directly above the cooling passages. This arrangement will insure that contact is made within a prescribed distance from the cooling channels and should result in cooler surfaces. It will also prevent welding at the edge of the electrode and reduce the possibility of cracking resulting from mechanical tensile stresses.
4. Decreasing the distance between the electrode face and the cooling channels to improve thermal conduction from the face.

Figure 4. - Interrupter electrodes after testing.

The modified interrupter has been manufactured and delivered for testing in the future.

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